**HYDROTHERMAL PLUMES AND HEATING EUROPA'S ICE SHELL FROM BELOW.** G. C. Collins[1] and J. C. Goodman[2], [1]Wheaton College, Norton MA (gcollins@wheatoncollege.edu), [2]Woods Hole Oceanographic Institution, Woods Hole MA (jgoodman@whoi.edu).

**Introduction:** Chaotic terrain disrupts the icy surface of Europa at a variety of scales, from large chaos areas over 100 km across to an abundance of small features less than 10 km in diameter. Models proposed for the formation of chaotic terrain [1-3] invoke some type of localized thermally-driven modification of the ice shell. Localization of heat may be caused by thermal diapirism within the ice shell [1,4], or focusing of heat from Europa's rocky interior, through a liquid layer, to the base of the ice shell. This latter possibility has been previously investigated from the perspective of how heat can be transmitted through the ocean via hydrothermal plumes [3,5], and from the perspective of how a plume could melt through the ice shell to produce chaotic terrain [2,10]. In this abstract we address hydrothermal plume behavior and ice shell melting, in an attempt to better understand how these processes may operate on Europa, and ultimately we wish to know if they leave visible evidence in Europa's surface geology.

**Hydrothermal Plumes:** Radiogenic heat and possibly tidal dissipation keep the temperature of the rocky interior of Europa above the temperature of the overlying ocean. The interior heat must be transmitted through the ocean and ice shell to be radiated into space. If heat sources are sufficiently localized at the top of the rocky interior, they will drive hydrothermal plumes in the ocean. Since the ocean is heated from below and cooled from above, it will convect, which will keep it well mixed and unstratified (unless the salinity is lower than 25 g/kg, see [6]). Thus to understand how heat can be concentrated at the base of Europa's ice shell, we need to understand the behavior of hydrothermal plumes in a rotating unstratified environment. Previous discussions of hydrothermal plumes in a Europan ocean have considered a rotating stratified environment [5] or a nonrotating environment [3].

We have performed a detailed scaling analysis of plumes in a rotating unstratified environment, and then carried out laboratory experiments of plumes in a rotating tank to verify our analysis and find unknown constants (summary in [7], full details in [8]). Based on this analysis, we can predict the behavior of hydrothermal plumes for a range of ocean depths and heat outputs. We consider a range of ocean depths from 50-170 km, based on gravity data [9] and an ice shell thickness less than 30 km. The appropriate range of heat output to consider is less constrained, so we adopt the values considered by previous authors [5,10] plus a margin, to give us a range of heat sources from 0.1 to 100 GW. Within this broad parameter space, we find very little variation in plume diameter. The diameter varies from 20 km at the thin ocean, low heat flux corner of our parameter space, to over 60 km at the thick ocean, high heat flux corner. There is also little variation in the maximum velocity of Coriolis-driven currents (3-8 mm/s), and these currents are too weak to drive ice raft motion in a melt-through model of chaotic terrain formation if a small amount of ice or slush remains at the surface [8]. Heat flux delivered by a plume to the base of the ice shell varies between 0.1-10 $W/m^2$.

**Plume Scale vs. Chaos Scale:** If chaotic terrain is formed by hydrothermal plumes melting through the ice shell, then the most common diameter of chaotic terrain areas will be the same as the diameter of the plume (or slightly larger, as eddies shed from the plume will carry heat away from the center), so we should expect that most chaos areas would be several tens of km in diameter. To understand why this is the case, we must examine how the ice shell melts in response to heat applied to its base. O'Brien et al. [10] have modeled this problem using an axisymmetric heat source at the base of the ice shell that is stronger at the center than the edges. This setup has the potential to make any diameter of melt-through between zero and the diameter of the heat source, since the ice shell will first be penetrated at the center of the heat source. However, they find that once the ice is penetrated, the diameter of the melted patch rapidly grows to equal the diameter of the heat source. This happens because there is a large amount of energy that goes into melting the subsurface ice, and once this is melted only a small amount of additional energy is needed to expand the edges of the melted surface patch. The area of the melted patch is proportional to the total energy delivered by the plume, minus a constant (to account for subsurface melting before penetration). For example, O'Brien et al. calculate that a 60 km wide heat source with a heat source of 50 GW can melt through 5.8 km of ice in ~1800 years, then after another 400 years the melt patch has grown to over a sixth of the heat source diameter. To make a melt-through patch smaller than 10 km, the plume would have to shut off between 1800 years and 2200 years.

The observed size distribution of chaotic terrain shows that the vast majority have diameters less than

15 km, and the observed number of areas keeps increasing down to ~8 km in diameter [11] or even smaller [12]. Is there a distribution of plume energies that could lead to the observed distribution of chaotic terrain diameters? If we assume that the energy of plumes, like many other geophysical systems, follows a power-law distribution, we find that we can match the size distribution of large chaos areas with the O'Brien model, but the model distribution asymptotes to a constant value at a diameter less than the plume diameter. All non-pathological distributions show this asymptotic behavior at small diameters, in opposition to the observations that the number of chaos areas increases with decreasing diameter. The only way to have the energy distribution of hydrothermal plume sources produce the observed size distribution of chaotic terrain areas is to include an infinite spike in the energy distribution function precisely at the energy required to melt through all the subsurface ice. Such an energy distribution for hydrothermal plumes on Europa is highly unlikely - why would volcanoes on the seafloor regularly vent for precisely the amount of time required to barely melt through the ice shell? Most likely there is some process other than melt-through which is controlling the size distribution of chaotic terrain.

**Effect of Plumes on Ice Shell:** Thus far our discussion has assumed that complete melt-through of the ice shell is a possible consequence of heating the base of the shell with a hydrothermal plume. However, complete melt-through is inconsistent with a simple energy balance between thermal emission from the surface and heating from below. To maintain melt at Europa's surface requires at least 300 W/m$^2$ [13], far more than the predicted heat fluxes from hydrothermal plumes in the parameter space outlined above. For the maximum heat fluxes predicted for plumes, tens of meters of ice remain unmelted at the surface in the equilibrium case. Previous calculations which predicted total melt-through at these same heat fluxes [10] suffered from insufficient vertical model resolution, see [13].

Hydrothermal plumes can supply heat to the base of the ice shell and perhaps significantly thin the ice. What effects could this have on the shell and the surface geology? We have argued that plumes and melt-through are unlikely to explain small chaos areas and the motion of ice rafts. Thinning the ice could drive ice raft motion if the rafts are carried on viscous basal ice which is flowing into the hole at the bottom of the shell. Isostatic adjustment of thinned ice could be observed as depressions in the surface. An example of this could be the E14 dark spot which is depressed by hundreds of meters [14], and is filled with low albedo material which could originate by cryovolcanism or by driving off frost due to enhanced heat flow in the thinned shell. The enhanced heat flux at the base of the ice shell from a hydrothermal plume could also trigger or enhance thermal diapirism, which has been proposed to form several surface features on Europa [1,4,15]. Heat from plumes could also produce localized areas of brine mobilization [16] which could contribute to the formation of chaotic terrain.

If there are localized heat sources at the base of the unstratified ocean, they will locally deposit that heat at the base of the ice shell above, at a characteristic scale. Do they have an effect on the observed geology of Europa? It appears that the scale of plumes cannot be reconciled with the melt through model to produce the observed population of chaotic terrain features. Perhaps plumes have a more indirect effect on the surface geology, by enhancing heat flow and by locally thinning the ice shell.

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